

Towards resilient water supply in centralized control and decentralized execution mode

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ABSTRACT

This paper shares a vision that sustainable water supply requires resilient water infrastructures which are presumably in the centralized control and decentralized execution (CCDE) mode with multiscale resilience. The CCDE should be planned based on the multiscale structure of water infrastructures, in which the systems are divided into a number of hierarchically organized subsystems. The CCDE allows independent execution of all subsystems under normal situations yet coordination of subsystems at different scales to mitigate any disturbances during failure events, i.e. the multiscale resilience. This vision is discussed in detail for water distribution systems (WDSs). Specifically, the conceptual design of the multiscale CCDE is described, and progress on understanding the multiscale structures in WDSs is summarized based on the literature review. Furthermore, a few theories consistent with the multiscale CCDE concept are discussed which include the decomposition theorems, fractal theory, control theories, and complex network theory. The next step in the vision will be to identify the optimal multiscale structure for the CCDE based on the best trade-off of different goals of WDS analysis and management. This process needs support from not only innovative modelling tools and extensive datasets and theories but also inspiring exemplar systems, e.g. natural systems.

Key words | centralized control and decentralized execution, decomposition theorems, multiscale resilience, sustainable water supply, urban water cycle, water distribution systems

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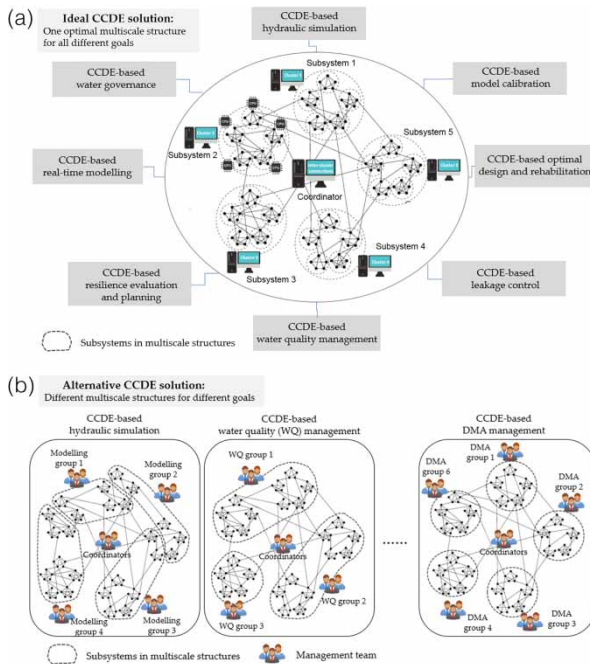
HIGHLIGHTS

- Centralized control and decentralized execution (CCDE) is proposed as a form for resilient water infrastructures.
- Planning CCDE based on multiscale structures in urban water systems realizes multiscale resilience.
- The design of CCDE is illustrated via a real-world water distribution system (WDS).
- Extensive studies on multiscale structures in WDSs are summarized.
- Theoretical supports for CCDE are identified.

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GRAPHICAL ABSTRACT



INTRODUCTION

Sustainable water supply, which is to meet various human needs for water with neither exhausting the water sources and the local economy nor having a long-term negative impact on the environment, needs resilient water infrastructures. Early visions on implementing sustainability focused on achieving ‘fail-safe’ infrastructures, which expects that a system will never fail and service delivery will always be maintained (Ahern 2011; Butler *et al.* 2016). However, this is an unrealistic expectation, since failure will not always be avoidable due to various factors, particularly unknown and unforeseeable threats (Wharton 2015; Butler *et al.* 2016). More recent thinking about change, disturbance, uncertainty, and adaptability is fundamental to the emerging science of resilience, the ability of a system to prepare for and adapt to changing conditions (e.g. persistent stress) and withstand and recover timely from exceptional disruptions (Ahern 2011; Folke 2016; Marchese *et al.* 2017) – i.e. systems that are ‘safe to fail.’ Specially, systems should be designed and operated, therefore, to overcome rather than

avoid failure altogether. The resilience of water infrastructures can thus be defined as the ability to minimize levels of service failure magnitude and duration and maximizes the time to failure impact over its design life when subject to exceptional conditions (Butler *et al.* 2016; Diao 2020). If a system is not resilient, any failure in it may cause considerable loss of water resources (e.g. from pipe breaks) and trigger huge costs for the recovery of the system. Resilience enhancement in water infrastructures is an emerging topic in both water research and industry, which has been recognized as an important need by both the World Health Organization (WHO & DFID 2009) and the United Nations (UN-Water 2010). Resilience enhancement has become a duty in the Water Act 2014 (in England and Wales) as noted by Ofwat (2012), which requires substantial investment to adapt water infrastructures.

Water infrastructures should be resilient, but how should resilient water infrastructures look like? Traditionally, water infrastructures are designed and managed on a

large-scale centralized form incorporating water supply, wastewater, and surface water treatment and distribution processes (Butler *et al.* 2010). In such a system, the coordination among water sectors and even within any single water system is inevitably very complex (Arora *et al.* 2015), particularly for large-scale systems. Moreover, long-distance delivery of water causes considerable energy consumption and high capital cost. For instance, around 80–90% of the cost of centralized sewerage is for transportation, with only 10–20% being for the actual treatment (Goodland & Rockefeller 1996; Maher & Lustig 2003). For these reasons, the decentralized system has been gaining increasing attention as a better solution (Larsen *et al.* 2013), which is to use independent smaller systems at a regional scale, e.g. a rainwater harvesting system at the community level. The decentralized system thus avoids or reduces the need for costly long-distance water transportation and can also significantly reduce water demand from the existing centralized system, e.g. by around 20% (Maher & Lustig 2003; Arora *et al.* 2015). However, the reduced flows and correspondingly increased concentration of their effluents are reported to have negative impacts on the operational performance of downstream infrastructures in several studies (Tjandraatmadja *et al.* 2005; Moglia *et al.* 2011a, 2011b; Marleni *et al.* 2012; Arora *et al.* 2015). Another issue of the decentralized systems is the difficulties in management, as it is harder to ensure the proper operation and maintenance of the systems by the owners. For example, US councils are given powers to enforce proper maintenance on the systems by implementing annual licence inspections, which is actually a centralized control and decentralized execution (CCDE) mode. Since both centralized and decentralized systems have advantages and disadvantages, it is an emerging topic to think of a trade-off solution, i.e. a combination of the two types of systems (Arora *et al.* 2015; Makropoulos & Butler 2018). However, the combination should result in a more resilient form of systems based on understandings of the resilience of both centralized and decentralized systems. Nevertheless, as just illustrated above, most of the comparisons between the two types of systems only consider the systems' performances under normal conditions. Accordingly, this paper will provide a vision of the conceptual design of resilient water infrastructures in the CCDE mode.

TOWARDS RESILIENT WATER INFRASTRUCTURES IN THE MULTISCALE CCDE MODE

This article shares the same vision that neither centralized systems nor decentralized systems will be the final solution for sustainable water supply. The reason is, in both types of systems, that resilience interventions are planned at monoscale, i.e. either for the whole system (the global scale) or for a region/subsystem in the system (the local scale). Both of the monoscale interventions have significant limitations. In the centralized system, a highly resilient subsystem design based on the local conditions may still be unable to perform properly due to failures on any critical route from the hub to the subsystem. However, the critical routes are difficult to identify due to the topological and behavioural complexity of WDSs. In decentralized systems, any failed subsystem can hardly get any support from any other subsystems, since there may have no pre-prepared interconnections.

The vision in this paper is, however, to use a CCDE form (Santicola 2005), i.e. all subsystems can work individually without disturbing each other significantly under normal situations. Once any failure occurs, the whole system can coordinate from a higher scale to ensure the failed system gets support, e.g. coordination from the subsystem scale to provide alternative path(s) to serve the failed system from other subsystems. This mode will avoid/minimize the long-distance transportation of water during normal conditions yet have the flexibility of centralized coordination among subsystems during failure events. The CCDE has been regarded as critical for the organization and employment of airpower in a strategy research project carried out by the U.S. Army War College (Santicola 2005). Actually, there are plenty of CCDE examples in common daily life too. For example, it is a common case that a multiunit organization that is geographically dispersed with identical products or services, such as retail stores or post offices, develops strategies centrally and implements them locally which are the right balance between global standardization of the units and local adjustment (Eriksson & Gustavsson 2013). Again, the recent COVID-19 pandemic also proves the necessity of the CCDE scheme, i.e. a centralized control strategy with different tiers of local lockdown rules.

Hence, the CCDE is a multiscale solution that may realize multiscale resilience, i.e. the ability to coordinate

different scales within a system to jointly cope and mitigate risks on any single scale (Figure 1), which is the feature of a complex resilient system (Mehaffy & Salingaros 2015). As Figure 1 shows, the system has both horizontal fit (interactions among components within each scale) and vertical fit (cross-scale interactions) (Bodin 2017) that allow the system to coordinate subsystems in each scale and different scales to cope with any disturbances. For example, any region should not extract as much groundwater as it can to safeguard itself from being left with nothing if the other regions were to maximize their extractions. Moreover, during an emergency, each region should be able to supply water to the nearby regions (the horizontal fit), i.e. each region needs to be responsible for not only its own water users but also the other regions and the whole system (the vertical fit). To realize such a vertical fit, the capacity of water infrastructures in each region should be decided by using a multiscale planning and governance that considers benefits and duties of each level of the system, e.g. the households, regions, and the city. Undoubtedly, the multiscale structure needs to be decided very carefully. It may not just include global, intermediate, and local scales, but instead many scales. Within each scale, the sizes of subsystems should be carefully planned too. Furthermore, the system should be more resilient if each subsystem is in the form of CCDE as well, i.e. a multiscale CCDE system in which the CCDE is applied not only to the whole system but also to each subsystem at each scale. However, the concept of CCDE with multiscale resilience is mainly at a proof-of-concept stage, and thus worthy of explorations in a systematic way, as a part of the journey towards revealing the ultimate form of resilient water infrastructures. In the next section, a detailed example is provided to illustrate the CCDE design for a water distribution system (WDS).

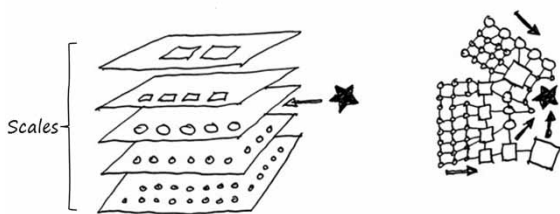


Figure 1 | A complex resilient system coordinates its multiscale response to a disturbance on any single scale. Reproduced from Mehaffy & Salingaros (2015).

TOWARDS RESILIENT WDSS IN THE MULTISCALE CCDE MODE

The conceptual design of multiscale CCDE

WDSs are lifelines of our society for the safe and secure provision of drinking water (USEPA 2005; Zhan *et al.* 2020). Studies on the resilience of WDSs are at an early stage. Thus far, the efforts mainly focus on developing a method to measure the resilience of WDSs by considering failure states and identify the key system components and states that result in high or low resilience. As for resilience intervention planning, few studies have been carried out to evaluate the impact of transitions from a centralized system to a decentralized system (Sitzenfrei *et al.* 2013a). However, no research has been carried out to systematically explore the resilience of the CCDE form to the author's best knowledge. With the same vision as described above, using the multiscale CCDE form for WDSs would not only improve the resilience of WDSs but also improve the efficiency and results of any modelling and analysis of WDSs and thus realize more reliable and efficient analysis, management, and control of WDSs. As Figure 2(a) shows, the multiscale CCDE WDS can take such a form. The whole system is virtually/practically decomposed into a number of subsystems, and each subsystem can be further divided into a number of subsystems. Hence, the WDS is viewed as a number of hierarchically interconnected subsystems, and each hierarchy level refers to a scale, i.e. the multiscale structure. The CCDE is then applied not only to the whole system but also to every subsystem at each scale.

The design concept of CCDE is further illustrated via the C-Town (Figure 3), a benchmarking real-world WDS consisting of five subsystems (Ostfeld *et al.* 2011) that allows coordination of the system at the subsystem scale. However, the current form of C-Town is well designed based on the conventional design concept but not the CCDE concept and thus does not allow flexible coordination among subsystems. Specifically, in the current system, water is first pumped from a reservoir (S1) to Subsystem 1 and two tanks connected to it, and then to four Subsystems 2–5 and their own tanks via booster pump stations (P2–P5) configured at the inlet of each of the four subsystems, respectively (Figure 3(a)–3(c)). Hence, the water supply of

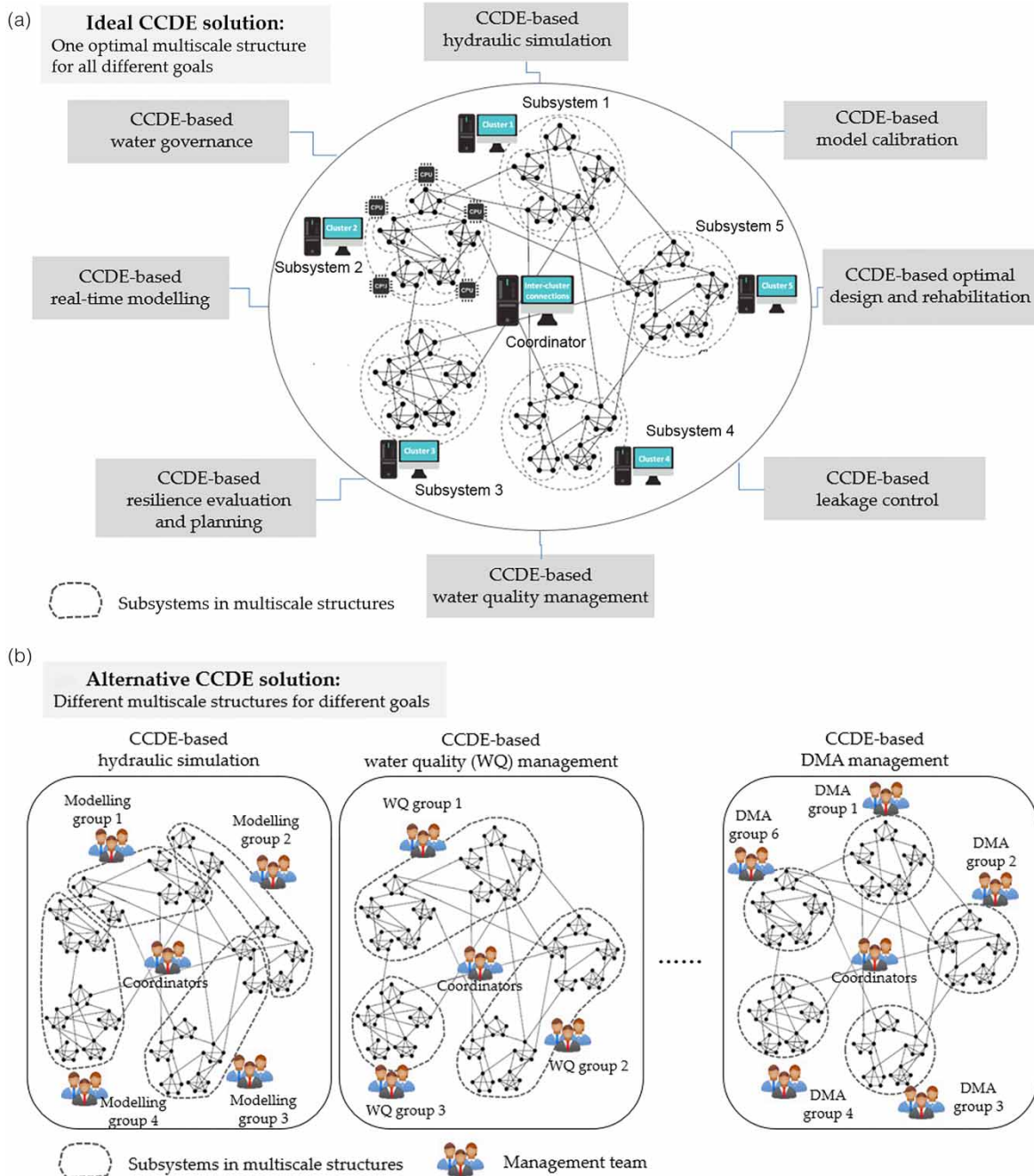


Figure 2 | Conceptual designs of the multiscale CCDE WDSs.

all Subsystems 2–5 relies on Subsystem 1, which requires delivery of water over long distances under normal conditions. As for exceptional conditions, if any locally critical pipe in Subsystem 1 (e.g. any pipe on the path from the reservoir to the system as annotated in red colour in Figure 3(d))

fails and is not fixed in a timely manner, such a failure will eventually result in out of water supply in the whole system (i.e. global scale impacts). To cope with such a failure, it needs all the subsystems to coordinate, but in the current form, Subsystem 1 has to keep serving both itself and the

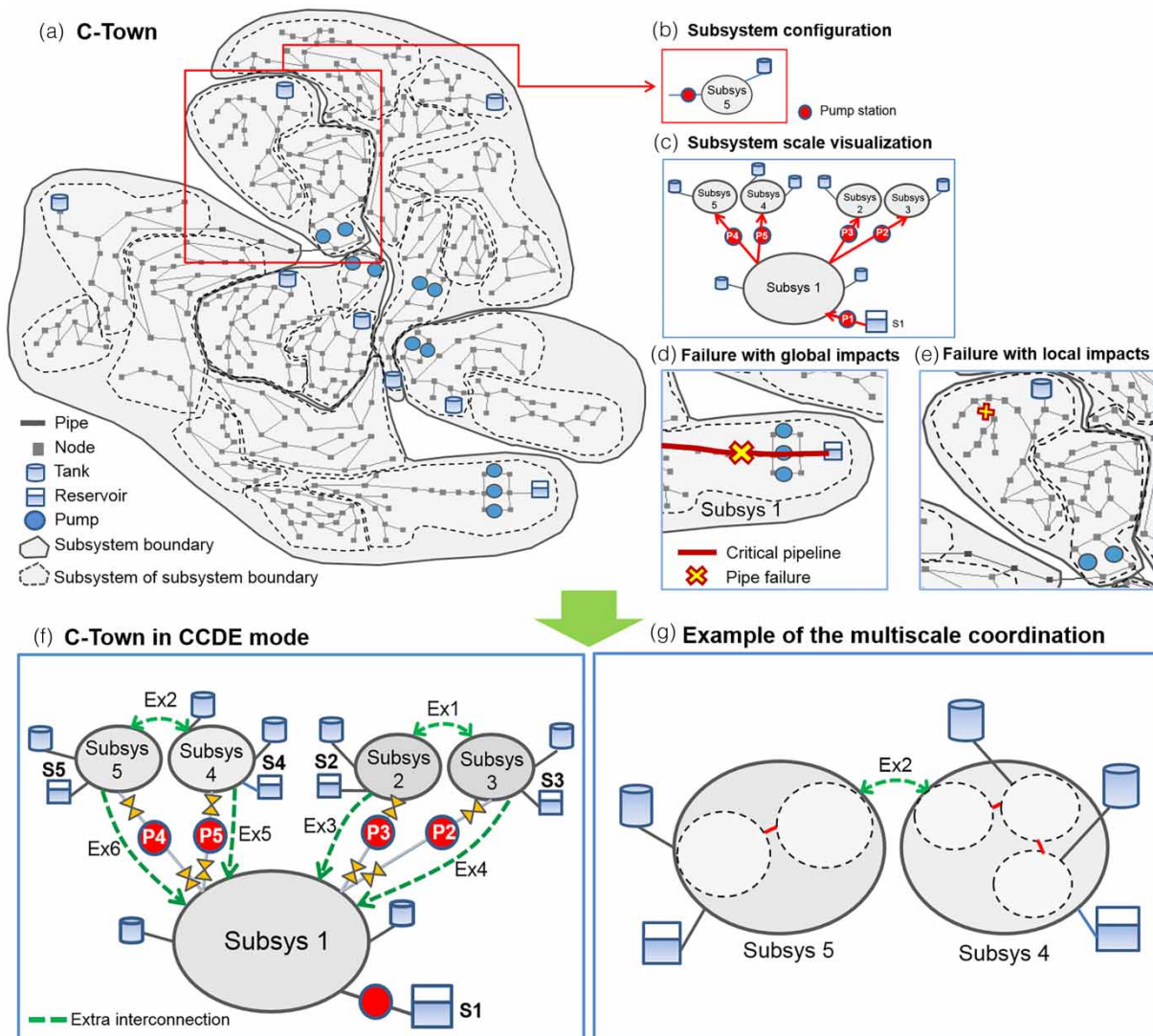


Figure 3 | An example for illustration of the conceptual CCDE WDS design. Please refer to the online version of this paper to see this figure in colour: [doi:10.2166/aqua.2021.162](https://doi.org/10.2166/aqua.2021.162).

other subsystems using its own tanks until drained, as Subsystem 1 cannot receive any supply from any subsystem at downstream. Furthermore, although some local pipe failures in Subsystems 2–5 may only affect local users (Figure 3(e)), some other types of local failure such as excess demands (e.g. firefighting demand) will still require long-distance delivery of water from Subsystem 1 and thus cause a global impact on the system. Apparently, such a one-way coordination is problematic. Hence, one solution would be to convert the C-Town into the CCDE mode if it is feasible to provide each of the Subsystems 2–5 with a local water source (S2–S5 in Figure 3(f)).

As shown in Figure 3(f), the CCDE form enables all subsystems to operate individually under normal condition (e.g. Subsystems 2–5 do not have to rely on Subsystem 1) by using their own water sources (S1–S5) and thus avoids long-distance delivery of water. However, the existing interconnections between Subsystem 1 and the others (the interconnections where the pump stations P2–P5 are located) need to be preserved. Under normal conditions, these interconnections can be isolated from the system by closing valves at both ends, while during exceptional conditions, they will be used for maintaining resilience. For example, if any of Subsystems 2–5 cannot meet its demand due to any

local failures (e.g. loss of connections to water source and drained tank), it can still be fed from Subsystem 1. Moreover, the resilience of the system can be further improved by adding new interconnections (Ex1–Ex6). Specifically, links between Subsystems 2 and 3 (Ex1) and between Subsystems 4 and 5 (Ex2) can be added to allow bi-directional water delivery from one subsystem to the other whenever necessary. Similarly, we can also allow other subsystems to feed Subsystem 1 by adding by-pass pipe (Ex 3–Ex6 in Figure 3(f)) in each booster pump station, which will open to let water travelling backward whenever necessary. On the one hand, these interconnections ensure that the subsystems at the same scale can coordinate among each other to cope with exceptional conditions, i.e. the horizontal fit. On the other hand, appropriate coordination at the subsystem level will reduce the total amount of water shortage in the whole system (global scale) during any failure event, i.e. the vertical fit (local coordination reduces overall impact globally) (Diao 2020).

To ensure proper coordination among subsystems, the design of each subsystem (e.g. the capacity of water source, tank, and pipes) cannot be done only based on the subsystem's local condition. The capacity of water sources and tanks needs to consider not only the water demand for the local people but also the demand of the other subsystems to feed (under exceptional conditions) and how long is the feed needed. For example, using all the current tanks in Subsystems 2–5 is sufficient for prolonging water supply in Subsystem 1 (water delivered via Ex3–Ex6) for 5 h during a failure event of loss of the connection to S1 (Diao 2020). If longer support to Subsystem 1 needs to be planned, then the tank capacities in the other subsystems need to be further enlarged. Similarly, the pipes (at least the important transmission lines) should have extra capacity for delivering the extra demand to the other subsystems. An example is shown in Figure 3(g). The pipes connecting different subsystems and subsystems of subsystems and the pipes inside each subsystem of subsystems all need to jointly work together to ensure water supply to both their local customers (the pipes' local role) and the other subsystems whenever necessary (e.g. the cross-scale role), which refers to the vertical fit as well, i.e. a multiscale resilient mechanism in which local single components support each other and also the subsystems of subsystems, subsystems of subsystems support each other and also the subsystems, and subsystems support each other and also the whole system. Note that the

conversion from traditional mode to the CCDE mode may not necessarily require tremendous increase in the WDSs' capacities and thus the costs. This is because traditionally the trunk mains were already oversized to be able to deliver a large amount of water to other parts of the system over long distance. These pipes can play the role as key interconnections among subsystems. Hence, rehabilitation will be carried out mainly at the subsystem scale (e.g. to add extra interconnections for flexible coordination among some subsystems) and the subsystem of subsystem scales (e.g. to create paths within subsystems as described before to enable the coordination).

Except the improved performance of the system, the CCDE concept will also facilitate modelling-based analysis and management and control of the system. At the design and planning stage of the CCDE form, interdependency analysis at the subsystem scale will be helpful for the simplification of the process, i.e. test how the status change (e.g. change of pipe sizes or open/close status of pipes) in one subsystem may affect the performance of the other subsystems. For example, when planning the coordination (via Ex1) between Subsystems 2 and 3 in C-Town, it is unnecessary to consider Subsystems 4 and 5. This is because there are no direct interactions between the two sets of subsystems due to their regional distance and the C-Town's design. Thus, any status changes in Subsystems 4 and 5 have no/marginal impacts on Subsystems 2 and 3, and vice versa. Once the CCDE design of C-Town is implemented in practice, for daily operational control and management, the CCDE form allows each subsystem to be modelled and analysed individually under both normal conditions and exceptional conditions. Although under exceptional conditions there will be interdependences among subsystems via their interconnections (i.e. Ex1–Ex6 in Figure 3(f)), modelling the subsystems separately is still feasible (e.g. separate calibration of each subsystem) as long as flow rates and nodal pressures of the interconnections are measured (e.g. via flow meters and pressure loggers on site) to define the boundary conditions of each subsystem.

Progress beyond the conceptual design

Although the multiscale CCDE of WDSs is still at a conceptual stage, the inherent multiscale structure in WDSs has been identified and extensively studied, which is the basis

of planning and management and control of the multiscale CCDE. So far, the multiscale structure has been used to significantly improve WDS analysis and management in many different tasks, including model calibration (Alvisi & Franchini 2010; Diao *et al.* 2010), hydraulic simulation (Zecchin *et al.* 2012; Diao *et al.* 2013), criticality analysis (Diao *et al.* 2014a; Ulusoy *et al.* 2018), water quality analysis (Perelman & Ostfeld 2011; Qiu & Ostfeld 2020), optimal design (Swamee & Sharma 1990; Zheng *et al.* 2013; Diao *et al.* 2015; Perelman *et al.* 2015; Sitzenfrei *et al.* 2020), asset management (Christodoulou *et al.* 2012; Wu *et al.* 2016; Abokifa & Sela 2019), and real-time demand estimation (Rana *et al.* 2018, 2020). The main strategies for all these studies are similar, which is to systematically decompose a WDS system following the multiscale structure into a series of simpler and smaller subsystems that are solvable more efficiently in parallel and/or in sequence. Once each subsystem is solved, they will be coupled to get the result of the whole system. If the result is unsatisfactory, the process will be repeated to improve the result iteratively until satisfied. The outcomes of these studies are consistent with the CCDE-based modelling analysis and management and control (Figure 2) and thus are strong evidence demonstrating that the multiscale CCDE may work as expected to help every aspect of WDS analysis and management. Such a mode also allows water companies to divide their whole team into groups based on the number of subsystems in the WDS (i.e. CCDE-based water governance). Each group will only need to focus on its own subsystem and be coordinated by the team responsible for simulating inter-subsystem connections (i.e. the connections connecting different subsystems).

It has been revealed that there are many different multiscale structures in WDSs, e.g. the multiscale structure of water supply zones planned based on urban morphology (Diao *et al.* 2012), water quality zones (Perelman & Ostfeld 2011), water demand zones (Rana *et al.* 2018, 2020; Diao *et al.* 2019), and pressure zones (Walski *et al.* 2003). Apart from these spatial multiscale structures, temporal multiscale structure has been identified too (Christodoulou *et al.* 2012; Cheifetz *et al.* 2017; Geelen *et al.* 2019). All of these structures have been used to facilitate the analysis of WDSs and below are a few examples.

For leakage reduction, the multiscale structure of water supply zones is used to provide a reference for district

metered area (DMA) planning (Sempewo *et al.* 2008; Di Nardo & Di Natale 2011a, 2011b; Herrera Fernandez 2011; Diao *et al.* 2012; Ferrari *et al.* 2014; Scibetta *et al.* 2014). With the inflow and outflow of each subsystem monitored, the water audit for the whole system can then be converted into auditing of a number of much smaller subsystems. This change significantly improves the opportunities to identify hidden pipe bursts in WDSs. For example, the software for automated localization of leak points in DMAs based on hydraulic modelling (Borovik *et al.* 2009) has been adopted by Affinity Water ('the largest water-only supplier in the UK') as standard practice for hidden leak detection in their WDSs since 2010 under the coded name, PlaN. The company has achieved 100% success after applying the software to 30 DMAs (a hidden leak will be found wherever the software shows), and now the PlaN is rolling out to 100 DMAs.

The multiscale structure of water quality zones is used to guide sensor placement in WDSs, which aims to minimize the impacts of any contaminant intrusion events, e.g. minimize the time of detection and the volume of water polluted via early warning and quick identification of the pollution source. Perelman & Ostfeld (2011) divided WDSs into strongly and weakly connected clusters according to the flow directions in pipes to provide guidance for sensor placement. Similarly, Mandel *et al.* (2020) clustered a real-world WDS into quality zones that help better understanding the system's operation and analysis of water quality events. Recently, Qiu & Ostfeld (2020) also proved that coordination among DMAs can facilitate water quality management.

The multiscale structure of water demand zones is created based on spatially variable demand patterns in WDSs. Rana *et al.* (2018, 2020) showed that using the water demand multiscale structure can improve the accuracy of real-time demand estimation, which is crucial for the real-time management of a WDS for the minimization of operating cost, emergency response, and water quality maintenance. Considering the variation of demand patterns in different subsystems improves the resilience of WDS design too. The traditional design of WDSs uses a uniform demand pattern for the whole system, and thus the system operation might not reach the expected performance due to the difference between the design flow scenario and the real situation. It is found from a few case studies that WDS systems designed by using water demand zones may

have lower capital cost (e.g. about 4.4% reduction) when subsystems with higher peak demands are closer to the water source and vice versa, longer average water retention time (e.g. can be 7.45 h longer), and nearly identical pump operating costs as long as the same average demands are applied (Diao *et al.* 2019).

Future work

Based on the multiscale structures identified above, the journey to achieve the multiscale CCDE for WDSs requires efforts at least from three aspects: modelling tools, data, and theories.

Modelling tool

The multiscale CCDE needs to be designed and evaluated by modelling tools with the corresponding multiscale analysis function. As described above, several multiscale structures have been revealed by various methods using network topologies, e.g. the modularity method, box-covering method, k-means clustering method, and spectral clustering (Herrera Fernandez 2011; Diao *et al.* 2012, 2016; Giustolisi & Ridolfi 2014; Di Nardo *et al.* 2016; Khoa Bui *et al.* 2020). The methods partition networks into subsystems by using various metrics and thus may have different results. For example, the modularity method divides a network by maximizing the modularity index (Q) (Figure 4(a)) to create a division that there are dense connections within subsystems but sparse connections between different subsystems (Clauset *et al.* 2004; Diao *et al.* 2012; Giustolisi & Ridolfi 2014) (Figure 4(a) and 4(b)). Instead, the k-means clustering method proceeds partitioning by minimizing squared Euclidean distances (Khoa Bui *et al.* 2020). Even the same method is used, the multiscale structure may still vary. For instance, depending on different weighting schemes used to the topologies, the modularity method generates different divisions (Giustolisi & Ridolfi 2014) (Figure 4(c)). Hence, it is worth exploring the possibility to develop a generic framework to identify the optimal multiscale structure that can preserve all/main good features of WDS (e.g. modularity and fractality) and meet all critical requirements for management and operation (e.g. leakage control, water quality control, and energy saving). Particularly, coordination within each scale

(horizontal fit) and among scales (vertical fit) to realize CCDE and multiscale resilience need to be optimized. The optimization can be done by first optimizing interactions among subsystems and progressively downscale to subsystems of subsystems until single components. At any subsystem level, we can evaluate how increased resilience in critical subsystems may affect the whole system and the interactions, and vice versa. For instance, Figure 5 is an example of a benchmark WDS with a complex layout (named as Exnet). The complexity makes it rather difficult to identify the key mechanisms and components of the system. However, through virtual decomposition of the system into subsystems and creation of an aggregated visualization by viewing each subsystem as a shape, it can easily identify the main trunks of the system, the places where there is lack of interconnections among subsystems, and places with ‘redundant’ connections. The same procedure is repeatable for each subsystem by dividing them into subsystems of subsystems.

Thus, the process will reveal: (1) how the resilience interventions can be planned on a scale-by-scale and subsystem-by-subsystem basis (e.g. from resilient community to resilient bigger regions, and finally to resilient urban water systems); (2) how to coordinate different scales to minimize failure impacts; and (3) what is the optimal structure and scale for CCDE. The optimal multiscale structure is likely to be a trade-off of different structures resulted from different goals, since it has been revealed that increased resilience in one aspect may decrease resilience to another (Diao *et al.* 2016). If an optimal multiscale structure fulfilling all purposes is not achievable, the alternative plan will be to identify the optimal multiscale structure for each different goal (e.g. multiscale structure for hydraulic simulation and multiscale structure for water quality management), respectively, as shown in Figure 2(b). Apart from the spatial multiscale structure, the temporal multiscale structure (Christodoulou *et al.* 2012; Cheifetz *et al.* 2017; Geelen *et al.* 2019) should be considered, which are not yet extensively studied.

Data

The rapid development of the information and communication technology along with big data analytics is facilitating the development of a measurement–analysis–decision

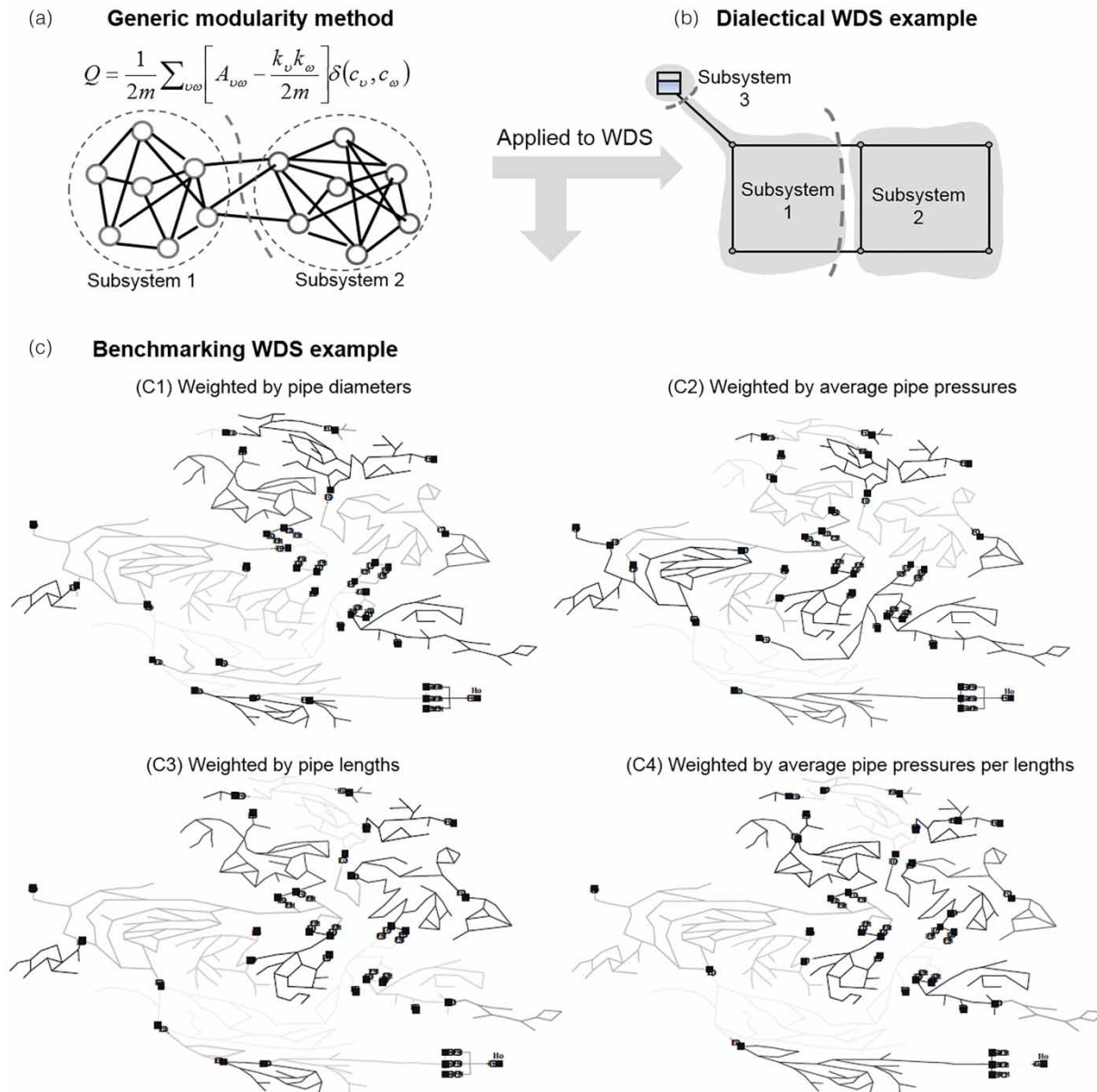


Figure 4 | An example of different multiscale structures obtained using different weighting schemes to topologies. Reproduced from Giustolisi & Ridolfi (2014).

framework (Ingildsen & Olsson 2015) that is shifting traditional urban water systems to smart water systems (Savic 2019; Giudicianni *et al.* 2020). Collecting extensive datasets to support modelling-based analysis have been increasingly used. The traditional asset management is now based on a geographic information system (Sharvelle *et al.* 2017). Digital water metering at the household level is increasingly used by water utilities (Beal & Flynn 2015), which will significantly

improve water demand estimation and predictions. Furthermore, the emerging cheaper yet effective sensors (e.g. software sensors) will not only provide more data for model calibration but also improve operational control of the systems and increase the probability of timely detection of failure events (Ingildsen 2002; Schneider *et al.* 2020). A number of hydraulic models of benchmarking WDSs have also been made available for testing new solutions. For

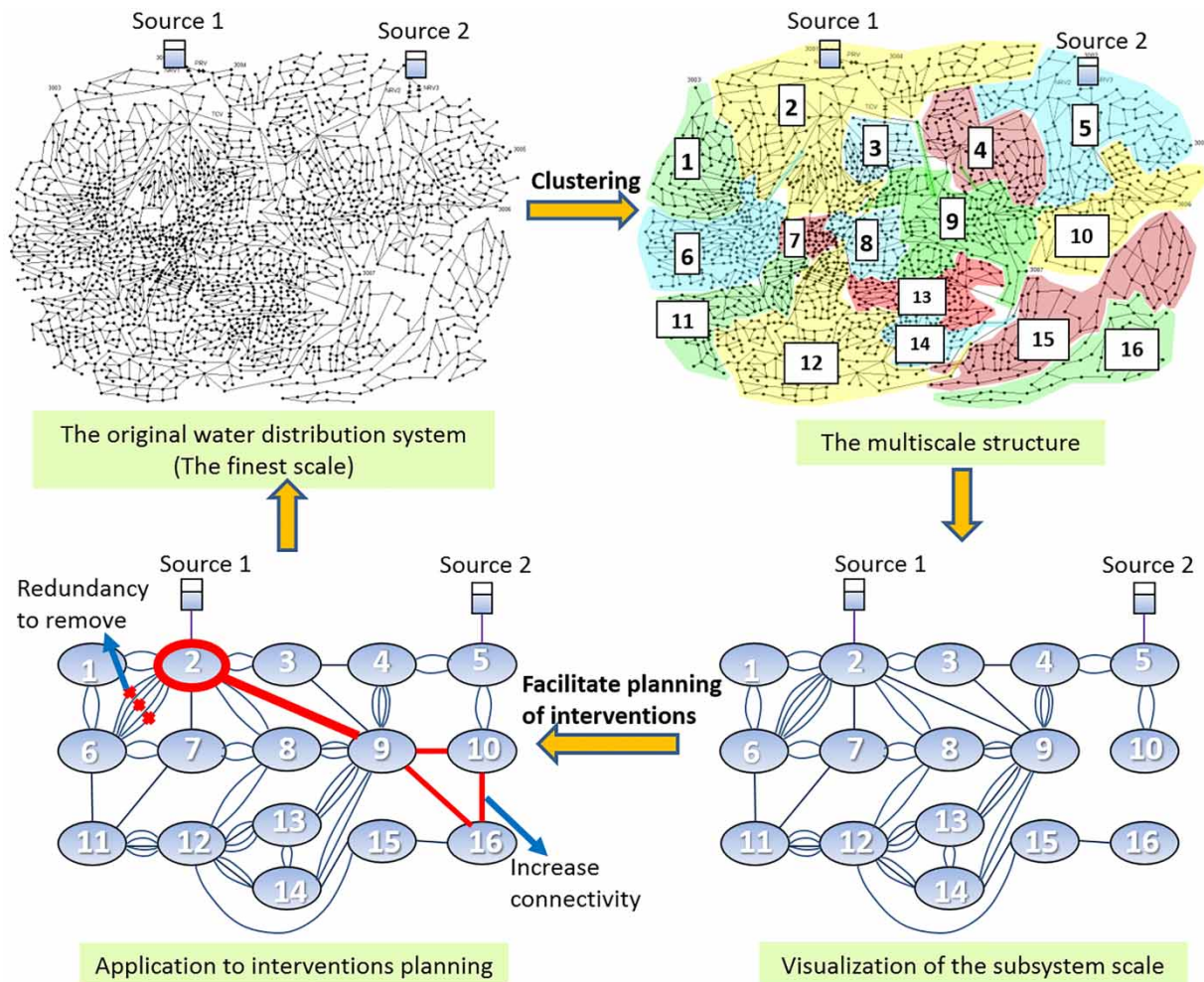


Figure 5 | An example of using the multiscale structure for resilience interventions planning for a benchmark WDS.

example, there are about 20 benchmarking WDSs ranging from small systems with simple configurations to much larger systems with complex topologies available from the Centre for Water Systems at the University of Exeter. In total, 48 WDSs with different features have been collected by the American Society of Civil Engineers (ASCE) Task Committee on Research Databases for WDSs, formed in 2013 and currently led by the Kentucky Water Resources Research Institute at the University of Kentucky (Hernandez *et al.* 2016). Tools are also developed to automatically generate synthetic WDSs based on real-world maps and design criteria, e.g. the WDS-Designer (Möderl *et al.* 2011; Sitzenfrie *et al.* 2013b) and DynaVIBe-Web (Sitzenfrie *et al.* 2010), WaterNetGen (Muranho *et al.* 2012), and HydroGen (De

Corte & Sørensen 2014). Based on these WDSs, extensive tests towards developing generic methodologies are becoming feasible.

Theories

Water engineering has been highly dependent on empirical methods, and thus the current trend is to develop evidence-based solutions based on computer models and increased availability of data. However, we can hardly be entirely confident about any solution unless it has been compared with all possible solutions or it is justifiable by theories. As it may always be difficult or even infeasible to check all possible solutions not to mention that there are unknown threats

on resilience, the exploration of theories is essential. The water industry in England and Wales focuses on the development of more generalized system theory-based indicators of resilience rather than specific infrastructure-based metrics, as reported by Lawson *et al.* (2020). Equally important, it will be worth answering the following questions: what are the ideal topological and operational patterns of an urban water system? Is there any theory that can prove the multiscale CCDE is the optimal form of resilient water infrastructures?

There is no theoretical proof of the optimal structure of resilient WDSs yet, even at the conceptual level. However, clues supporting the multiscale CCDE from different perspectives are found from the following theories applied in WDS analysis.

Decomposition theorems. Decomposition theorems for complex systems (Simon & Ando 1961; Simon 1962; Courtois 1985) define that system decomposition is a process of stabilization by dividing systems into communities with stronger internal connections than external connections (Salingaros 2001). These theorems are consistent with CCDE, i.e. a stable system should consist of a number of subsystems, although there should be denser connections within each subsystem and sparse connections among subsystems, the subsystems should be connected rather than running individually. Hence, a stable system may be neither centralized (dense long-distance connections among certain subsystems) nor decentralized system (no connections among subsystems). It has been revealed that the formation of multiscale structures in WDSs complies with the decomposition theorems (Diao *et al.* 2012), and the quality of the division can be measured using modularity (Clauset *et al.* 2004) as an indicator.

Fractality. Fractals have been identified as one of the most general features of many natural and artificial networks that exhibit self-similarity of the topological patterns, i.e. different parts of the system have similar structures to each other as well as to the whole system (Mandelbrot 1982; Song *et al.* 2006). WDSs have been recently proved as fractal too and it is observed that there is self-similarity among subsystems in terms of both their topological patterns and hydraulic behaviours (Diao *et al.* 2017; Di Nardo *et al.* 2017; Vargass & Saldarriaga 2019a, 2019b; Caldarola &

Maiolo 2020; Iwanek *et al.* 2020). Specifically, several properties comply with the power-law distribution regardless of the scale of the system, including the headloss (Diao *et al.* 2017), the sizes of the supply districts and the population within those districts (Krueger *et al.* 2017), the length of water pipes required to serve each customer (Krueger *et al.* 2017), and the node degree distribution (node degree is the number of links connected to the node) (Zischg *et al.* 2019). Furthermore, Ward *et al.* (2020) identified similar patterns in the water-sector organizational network for water governance. These facts are another support of the idea of multiscale CCDE regarding each subsystem should have the CCDE form as well which is similar to the whole system as well as the other subsystems.

Controllability and observability. Controllability and observability are dual concepts in the control theory. Controllability can find out the minimum number of actuators and their locations required to control all the states of the system; conversely, observability finds out the minimum number of sensors and their locations to supply all information necessary to estimate all the states of the system (Preumont 1997). These studies can thus guide the optimal placement of actuators and sensors in the multiscale structure of WDSs. For water quality management in WDS, the states of the system can be represented by using directed graphs for every time step. If the flow directions in the graphs are identical to the modelling results, controllability is applicable to identify the minimum number of actuators to fully control the water quality in the system. Contrarily, if flow directions reversed to modelling results are used, observability is applicable to identify the minimum number of sensors to fully monitor water quality events in the system. In WDSs, 30–40% nodes need to be placed with sensors to ensure the detectability of any contamination events no matter where it happens in the system (Diao & Rauch 2013). Although 30–40% coverage by sensors is too high to be currently practical, it is still important to know exactly how many sensors are theoretically required. The sensor locations can then be prioritized based on the available budget. Furthermore, the research on cheaper sensors will shed the light on fully monitoring of WDS. The link between controllability and multiscale structure is also explored. It is found that most of the critical inter-subsystem

connections (77%) also have at least one of its nodes being critical actuators (Diao *et al.* 2014b). This fact proves that there is consistency in different theories and methodologies, and thus the possibility of a CCDE form satisfying all or at least most of the theories.

Graph theory and complex network metrics. A number of topological metrics (connectivity, centrality, diversity, robustness, and modularity) have been used to understand the formation, structure, efficiency, vulnerability, and resilience of WDSs (Yazdani & Jeffrey 2011; Diao *et al.* 2012, 2014a, 2014b; Giustolisi & Ridolfi 2014; Meng *et al.* 2018; Giustolisi *et al.* 2019a, 2019b, 2020). The interplay between the metrics and hydraulic behaviours of WDSs is the recent focus of this topic. Giustolisi *et al.* have re-developed several complex network metrics, e.g. the modularity index (Giustolisi & Ridolfi 2014), centrality metrics (Giustolisi *et al.* 2019a, 2020), and betweenness (Giustolisi *et al.* 2019b) to take into account attributes and hydraulic behaviours of different components in WDS (e.g. nodal demand for nodes; length, diameter, and hydraulic resistance for pipes). Meng *et al.* (2018) analysed the correlations between resilience and six key topological attributes by using 85 WDSs with different sizes and topological features. So far, it has been unveiled that WDSs are sparse near-planar graphs whose structures largely resemble the surrounding urban areas supplied by the system (Yazdani & Jeffrey 2011), and the structures have several good features, e.g. high modularity (modularity index >0.3), fractality (fractal dimension >1), and resilience to random failures (Diao *et al.* 2014a, 2014b, 2016, 2017). The next will be to explore how to preserve these good features and meanwhile further improve resilience towards sustainable WDS design. For example, although WDSs have a multiscale structure, the inherent resilience is not multiscale resilience (Diao 2020). These are because the main function of traditional water pipeline systems is to deliver water from upstream to downstream (Walski *et al.* 2003, 2007). In WDSs, the water flow is from water sources (e.g. a reservoir) to end users and from large pipes to smaller pipes (Walski *et al.* 2003), i.e. from larger scale to smaller scale, and hence the downstream pipes (at smaller scales) are not expected to deliver water to upstream customers (at larger scales). However, the case study shows that adding extra connections that can

direct flow from smaller scale to larger scale provides flexibility in water supply coordination (e.g. allow subsystems at downstream to feed subsystems at upstream) and thus reduces the total amount of water supply shortage in the system during failure events of losing the connection to the reservoir (Diao 2020).

Biomimicry. Studies on good samples of other systems may inspire the optimal design of resilient WDSs, which is also the trend of multidisciplinary research. Actually, the development of engineering is not independent from biomimicry (e.g. the invention of airplane). The nature systems should be the best trade-off under the given circumstances and thus be good examples of illustrating how a complex system should evolve. For example, studies on the structure and evolution of biological networks (e.g. the blood circulatory system in human body) may be able to guide the optimal design of WDSs, e.g. by regarding the heart as a pump station and vessels as pipelines (Figure 6). At a smaller scale, studies on the detection of aneurysm flow in vessels may inspire the early detection of low hidden leakage flows in WDSs, which is a big challenge in leakage control in WDSs (Figure 6).

CONCLUSIONS

A resilient WDS is essential for sustainable water supply, and thus the resilient multiscale CCDE mode is worth exploring as a possible trade-off between centralized and decentralized modes. The CCDE mode is a multiscale solution, as subsystems running independently at a local scale under normal conditions will be coordinated to jointly mitigate any disturbance to the system under exceptional conditions, i.e. multiscale resilience.

Although both the multiscale CCDE mode and multiscale resilience are still at a conceptual stage, the multiscale structure of WDSs, which is the basis for planning the CCDE mode, has been extensively studied. It is found that understanding and utilizing the multiscale structure can improve analysis (both efficiency and quality of results) and management (e.g. inter-organizational water governance) of WDSs. Furthermore, the theories of decomposition

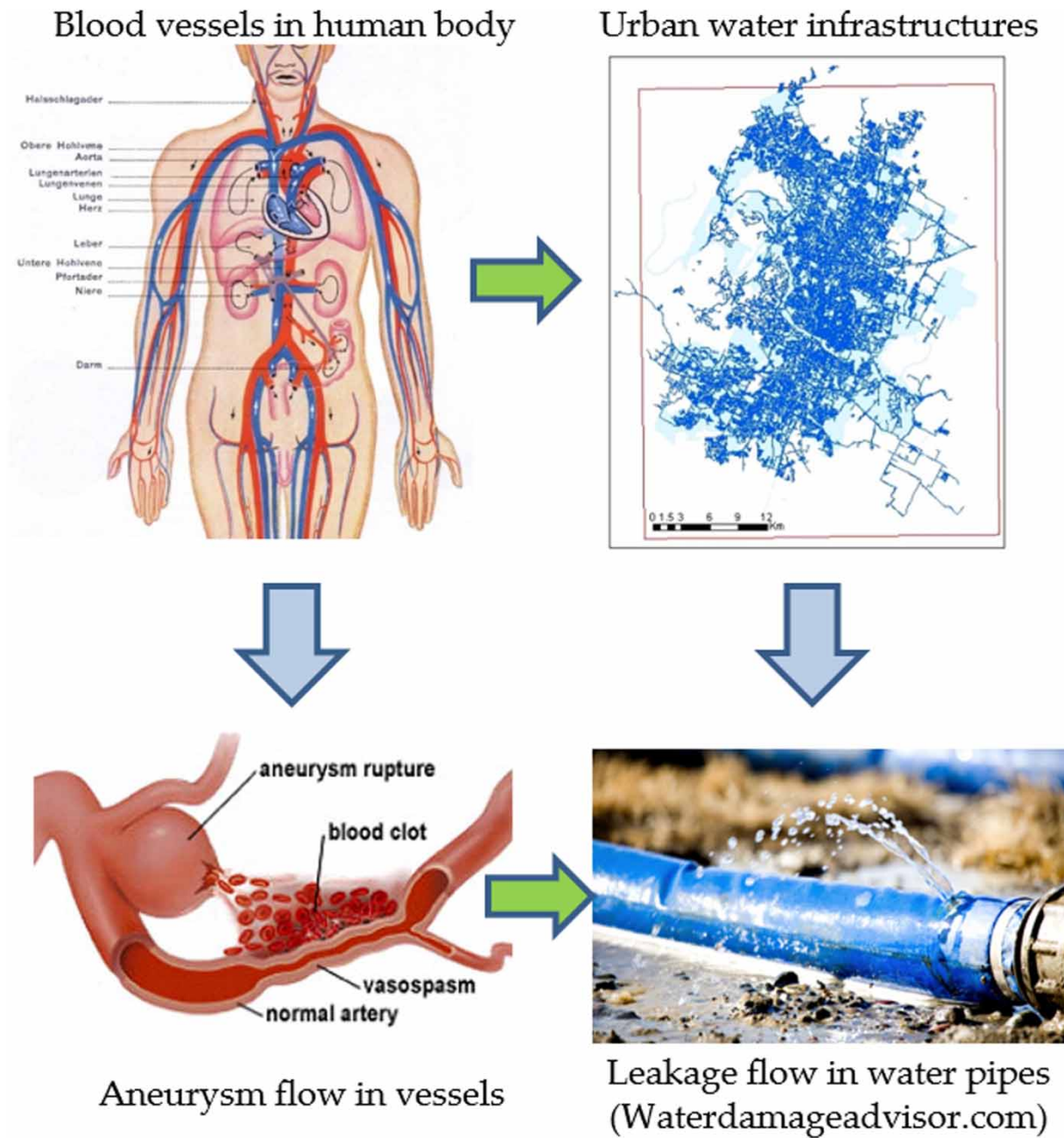


Figure 6 | Similar mechanisms and failure events in human blood circulatory system and WDS (Waterdamageadvisor.com).

theorems, fractality, controllability, and observability are also supporting the concept of multiscale CCDE.

The future study can focus on exploring the optimal multiscale structure and thus the optimal multiscale CCDE, which is likely a trade-off of structures required by different goals. For this purpose, extensive hydraulic

models of various WDSs need to be collected and tested by innovative hydraulic modelling tools with multiscale analysis functions. Moreover, theoretical supports need to be identified, e.g. by involving exemplars from different disciplines such as complexity and biomimicry.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories (<http://emps.exeter.ac.uk/engineering/research/cws/resources/benchmarks/>).

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